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ABSTRACT

Fifty-six percent of 46 residences monitored in the Spokane River Valley in eastern Washington/northern Idaho have indoor radon concentrations above the National Council for Radiation Protection (NCRP) guidelines of 8 pCi/l. Indoor levels were over 20 pCi/l in eight homes, and ranged up to 132 pCi/l in one house. Radon concentrations declined by factors of 4 to 38 during summer months. Measurements of soil emanation rates, domestic water supply concentrations, and building material flux rates indicate that diffusion of radon does not significantly contribute to the high concentrations observed. Rather, radon entry is dominated by pressure-driven bulk soil gas transport, aggravated by the local subsurface soil composition and structure. A variety of radon control strategies are being evaluated in 14 of these homes. Sub-surface ventilation by depressurization and overpressurization, basement overpressurization, and crawlspace ventilation are capable of successfully reducing radon levels below 5 pCi/l in these homes. House ventilation is appropriate in buildings with low-moderate concentrations, while sealing of cracks has been relatively ineffective.

INTRODUCTION

The Bonneville Power Administration (BPA) is involved in various programs that promote energy conservation through the implementation of house tightening weatherization retrofits and new construction standards in Pacific Northwest buildings. These measures tend to reduce the amount of natural ventilation occurring in buildings which in turn may impact indoor air quality by allowing certain air pollutants to accumulate. In conjunction with the programs, BPA offers passive radon monitoring to participating homeowners. If radon concentrations above 5 pCi/l are measured, BPA recommends that action be taken to reduce the level of radon to below 5 pCi/l. The only mitigation strategy currently recommended by BPA is the installation of an air-to-air heat exchanger. BPA will partially subsidize the cost of the equipment and installation in homes that have received BPA-sponsored house tightening. In an effort to find and demonstrate effective, low cost alternatives to the heat exchanger, BPA has sponsored this research project.

Earlier indoor air quality field survey studies conducted for BPA, included measurements of radon gas (^{222}Rn) concentrations in 20 commercial and institutional buildings in Spokane - Cheney, WA. and Kootenai County, ID., and in 69 new and existing homes in Spokane County, WA, and Kootenai County, ID. A review of the data indicates that a subset of one commercial and 46 residential buildings, roughly located in the Spokane River Valley of Washington State and the Rathdrum Prairie of Idaho, have indoor radon concentrations that are substantially higher than average. An examination of soils, domestic water supplies, and building materials strongly suggests that the high concentrations in these areas are related to the local subsurface soil composition and structure.

The average concentration for the 46 residences was 13.3 pCi/l with a median of 5.9 pCi/l. Twenty-six, or 56.5%, of the residences had concentrations above the BPA action level of 5 pCi/l and 20, or 43.5%, had concentrations above 8 pCi/l (National Council on Radiation Protection and Measurements Guideline - NCRP)[1]. This can be compared with a recent compilation of measurements made in 552 U.S. residences by Nero, et al.[2]. The data are approximated by a lognormal distribution with a GSD of 2.8 pCi/l. Their data implies that approximately 6% of all U.S. single-family housing has radon concentrations above 5 pCi/l and approximately 2% above 8 pCi/l. In another study by Thor of 267 BPA employee houses in the Pacific Northwest, the lognormally distributed data had a geometric mean radon concentration of 0.8 pCi/l [3]. Therefore, it was concluded that the Spokane River Valley/Rathdrum Prairie region has conditions favorable for creating high indoor concentrations and was a suitable area for the study of radon mitigation techniques.

Fifteen homes were selected for this investigation. In addition to providing an evaluation of the various techniques and researching the mechanisms of radon entry, another goal was to reduce the long-term average heating season radon concentrations to below 5 pCi/l in each house.

This is a preliminary report of findings from this on-going study.

METHODS

Fifteen homes with radon concentrations above 5 pCi/l were selected for this follow-up study to evaluate various radon control strategies. Fourteen were located in the Valley/Prairie area of eastern Washington and northern Idaho, while one was located along the west coast in Vancouver, WA. Two of the fourteen designated as "Control" structures to monitor seasonal changes of indoor radon concentrations throughout the study, have not yet received remedial action, but will at the conclusion of the project. Brief descriptions of each home are summarized in Table I. A variety of sizes, ages, and substructure types were included although there was only one home with slab-on-grade construction (EVA604) and no homes having only a crawlspace. Only two homes have combustion fuel heating appliances. Ten homes have central forced air furnaces that are located in a crawlspace or basement. As far as could be determined, none of the homes have foundation drain tile or evidence of basement water damage.

Most homes were visited in the summer of 1985 to collect water and soil samples and measure radon emanation from building materials. Water samples were drawn from an outside faucet into two one-liter polyethylene bottles. The bottles were returned to LBL and were analyzed at a gamma spectroscopic counting facility. Emanation rates from building materials were determined by sealing an inverted shallow aluminum pan containing three charcoal canisters at up to three floor and wall locations for approximately 36 hours. The charcoal canisters were also returned to LBL for gamma spectroscopic analysis of the adsorbed radon. Substructures were examined during a subsequent visit and probable radon entry locations were identified. From this survey, a tentative schedule of appropriate mitigation techniques was developed for each house. In some houses, several techniques were utilized for purposes of comparison. As the study has progressed, unsuccessful measures have been abandoned and others substituted. The following techniques were targeted for investigation and are now being evaluated.

TABLE I. HOUSE DESCRIPTION

House I.D.	Occupied Floor Area(m^2)	Heating System	Year Built	Floors Above Grade	Description of Substructure[(a)]
Northern Idaho/Rathdrum Prairie					
ECD026 Control	168	Electric Forced Air, Wood Stove	1972	2	Finished half-depth[(b)] basement ($60m^2$); with connecting crawlspace ($60m^2$)
ECD027	250	Wood Stove	1900	2	Full depth open soil basement ($66m^2$); small crawlspace ($21m^2$) and utility room slab on grade ($17m^2$)
ECD153	196	Electric Forced Air, Wood Stove	1975	1	Finished half-depth basement ($89m^2$); with vented, adjoining crawlspace($89m^2$)
NCD077	189	Natural Gas Forced Air	1984	1	Unfinished full depth basement ($63m^2$) with adjoining crawlspace ($62m^2$)
Eastern Washington/Spokane River Valley					
ESP101	204	Baseboard Electric	1969	2	Finished full-depth basement ($53m^2$) and half-depth basement ($47m^2$)
ESP108 Control	327	Heat Pump Forced Air,	1955	1	Finished full-depth basement ($183m^2$)
ESP109	166	Electric Forced Air, Wood Stove	1978	1	Finished half-depth basement ($78m^2$)
ESP111	235	Electric Forced Air	1978	2	Unfinished full-depth basement ($56m^2$) and finished half-depth basement ($54m^2$)
ESP113	203	Baseboard Electric	1968	2	Finished half-depth basement ($87m^2$) and slab on grade ($15m^2$)
ESP116	189	Electric Forced Air, Wood Stove	1974	1	Semi-finished full-depth basement ($95m^2$)
ESP119	158	Electric Forced Air	1977	2	Finished half-depth basement ($52m^2$) with adjoining crawlspace ($49m^2$)
ESP120	220	Baseboard Electric	1920	2	Field stone and mortar walls of semi-finished full depth basement ($65m^2$)
ESP121	176	Electric Forced Air	1976	1	Finished half-depth basement ($84m^2$)
MSP204	177	Electric Forced Air W/AAHX	1984	1	Treated wood walls of unfinished full-depth basement ($56m^2$) with adjoining crawlspace ($75m^2$)
Vancouver, WA					
EVA604	79	Baseboard Electric	1952	1	Slab on grade ($79m^2$)

(a) All substructure floors and walls are poured concrete unless indicated otherwise
(b) Sometimes referred to as "Daylight Basement", generally 1.0-1.5 meters below grade

1) **Sealing of Cracks and Holes.** [4]

To reduce the number of radon entry locations, asphaltic and mortar patch compounds were used to seal accessible cracks and holes in the substructure surfaces of five homes. Surfaces were first prepared by chipping and cleaning. Defects ranged from hairline cracks to large (40 cm. diameter) holes through slabs.

2) **House Ventilation with Heat Recovery.** [5]

New, ducted, central air-to-air heat exchangers (AAHX) were installed in the occupied basements of two homes. One home with an existing, poorly installed AAHX had delivery and return ducts modified.

3) Sub-Surface Ventilation. [6,7,8,9]

In five homes, soil beneath the basement floor is being ventilated through 3" PVC pipes that were placed through the slab in up to four locations per house. The pipes terminate approximately 30 cm below the slab in a 60 cm diameter dry sump backfilled with washed gravel. The pipes are routed either singly or manifolded with other pipes to the outdoors. Here, centrifugal blowers capable of developing greater than 125 pascals pressure head and greater than 25 l/s flow rate are installed on the pipes. Soil gas is then either exhausted from below the slab surface by depressurization and vented outdoors or outside air is blown into the sub-surface soil by overpressurization.

4) Overpressurization of the Basement.

Basements in six homes were first tightened to reduce air leakage to the upstairs and outside, then pressurized with respect to the interstitial soil pore pressure with a 100 - 200 l/s fan. The fan pulls air from the upstairs and exhausts into the basement. These homes all have closeable doors to the basement that are kept shut with spring - hinge closers.

5) Crawlspace Sealing and Ventilation. [10]

In addition to providing natural ventilation for crawlspaces, staged sealing and mechanical ventilation are being investigated. A crawlspace soil floor has been sealed with a plastic membrane. In two homes, the house was sealed from the crawlspace. An axial fan was used to evaluate combinations of ventilation, pressurization, and depressurization in one crawlspace.

In mid-October, 1985, the first homes were set up with monitoring equipment including an EPROM data logger that continuously records 30 minute average indoor and outdoor temperatures, wind speed and direction, and radon concentrations. The continuous radon monitor (CRM) was designed and built at LBL and was installed at a central location of the most frequently occupied floor of the house. Additional CRM's were moved from house to house to monitor concentrations in basements and crawlspaces. Continuous monitoring of basement - soil pressure differences and furnace operation occurred in three homes.

Measurements of ventilation and other indoor air pollutants were made to study the effects of the radon mitigation strategies on other indoor air quality parameters. Seven day average measurements of formaldehyde (HCHO) and water vapor (H_2O) using passive samplers; respirable suspended particles (RSP) using a pumped, time-weighted average collection system; and ventilation rates using the passive perfluorocarbon tracer (PFT) technique were periodically conducted. Also during these periods, house depressurization blower door tests were run and daily occupant activity logs were completed. Independent meteorological observations for barometric pressure, precipitation, dry bulb temperature, and wind speed and direction, have been collected from the nearest National Weather Service station.

Soil gas grab samples were collected in 100 cc Lucas alpha scintillation flasks and counted with portable photomultiplier tube equipment. The soil gas is drawn from 1 - 1.5 meter long pipes driven into the soil at two locations at each house. They are generally no closer than one meter or farther than seven meters from the houses. An evacuated scintillation flask is then filled with gas from the pipe which had been purged with a small hand pump.

As a means of evaluating diagnostic techniques and identifying radon entry locations, scintillation flask samples were taken from various building volumes including wall cavities, floor drains, and sealed rooms and compartments. The radon concentrations in these spaces were then "mapped" on a floor plan of the house as an indication of the most important areas of radon entry and to provide information before and after mitigation. Pressures (using a micromanometer), flow rates (using hot wire anemometers and pitot tubes), and temperatures were periodically monitored in the pipes of the sub-surface ventilation systems and in the ductwork of the air-to-air heat exchangers. Spot measurements of the electrical consumption of blowers and fans have been made. Data on the labor effort and materials required for the installation of the various strategies were also collected.

After removal of the continuous instrumentation, monitoring using four type SF TrackEtch® detectors in each house began in March, 1986 - June, 1986 and is being repeated over the summer, June - August, 1986 to follow up on the short-term reliability and effectiveness of the techniques.

DISCUSSION

Eight of the homes originally had winter season radon concentrations averaging greater than 20 pCi/l, with house ESP120 having the highest concentration of 132 pCi/l (see Table II). Radon concentrations in the summer were lower in all homes, with an average winter - summer ratio of 21.6 (std. dev = 8.9), ranging from a ratio of 32.9 (ESP111) to 3.8 (ESP109). Winter season values are the weighted average of intermittent continuous monitoring periods during the months November through March in 1984 - 1986. Summer levels were measured with two type SF TrackEtch® detectors exposed in selected houses from June - August, 1985.

TABLE II. RADON SOURCE AND INDOOR CONCENTRATION MEASUREMENTS

HOUSE ID	WATER SUPPLY SOURCE[a]	WATER SUPPLY RADON (pCi/l)	SOIL GAS[b] RADON (pCi/l)	BUILDING MATERIAL EMANATION[c] ($pCi/m^2/sec$)	INDOOR AIR (pCi/l) SUMMER 85[d]	INDOOR AIR (pCi/l) WINTER SEASON 84-86[e]
ECD026C	W	900	277-395	NA	1.1	17.2
ECD027	W	2820	294-464	5.13	3.8	45.0
ECD153	W	250	630-659	0.10	1.0	24.2
ESP101	M	550	314-393	0.21	3.5	27.6
ESP108C	M	630	340-487	NA	4.3	15.3
ESP109	M	670	NA	NA	1.8	6.9
ESP111	M	370	306-353	NA	0.9	29.6
ESP113	M	570	420-426	NA	3.7	23.0
ESP116	M	550	374-521	0.06	NA	23.6
ESP119	M	460	396-400	NA	NA	49.4
ESP120	M	500	311-610	0.23	11.9	132.0
ESP121	M	560	NA	NA	1.2	11.2
EVA604	W	610	620-626	0.05	0.9	10.4

(a) W = Well, M = Municipal

(b) Range of values obtained at a depth of 1.0 - 1.5 meters from December 1985 grab samples

(c) Maximum value of all floor, wall or other measurements

(d) Passive Monitors

(e) Average for intermittent continuous monitoring throughout the months November - March

As seen in Table III., air between basements and upstairs is often quite well mixed even in homes with electric baseboard heat, but is not always so between crawlspaces and occupied spaces.

The measurements of water radon concentrations and of radon flux from building materials (Table II.) indicate that radon entry by diffusion is not a significant source of the observed indoor air concentrations. Other researchers have found that the radon from tap water generally results in house air radon concentrations that are smaller by a factor of 10^{-4} [11]. Assuming an air-to-water ratio of 10^{-4}, the maximum contribution from any of the water supplies measured for this study is 0.3 pCi/l in house ECD027.

TABLE III. SUBSTRUCTURE - UPPER FLOOR RADON CONCENTRATIONS

HOUSE ID	HEATING SYSTEM[a]	RADON (pCi/l) - [STD. DEV.] UPSTAIRS	BASEMENT	CRAWLSPACE
ECD026C	FA	17.3[5.20]	-	17.2[7.36]
ESP106C	FA	15.4[1.80]	17.8[2.33]	-
ESP113	BB	3.7[1.72]	3.7[1.74]	-
ESP119	FA	49.4[8.69]	-	111.4[22.95]
ESP120	BB	106.1[35.0]	125.9[40.04]	-

(a) FA = Forced Air
BB = Baseboard Electric

The maximum building material flux rate of 5.13 pCi/m^2/sec (also in house ECD027) was measured at one of two locations on the concrete basement wall approximately one meter below grade level. The other measurement indicated a flux of 0.66 pCi/m^2/sec on this same wall material. The value of 5.13 pCi/m^2/sec is many times higher than that typically seen for exhalation rates from building materials (0.05 - 0.20 pCi/m^2/sec). While it is partially corroborated by the measurement at the other wall location in this building, this high flux may be a result of sampling error due to a poor seal between the sampling pan and the very irregular surface of the basement wall.

If this is the case, high radon concentration room air may have leaked into the sampling pan and contaminated the exposed charcoal. However, we cannot exclude the possibilities that this basement wall of heterogeneous materials, may contain significant radium mineralization, or that the obviously old, handmade wall is very porous, permitting considerable radon from the soil to pass through the wall material. A flux of 3.35 $pCi/m^2/sec$ was measured on the open soil floor. Assuming an exposed wall area of 62.5 m^2 emanating at the lower rate of 0.66 $pCi/m^2/sec$ and a floor area of 66 m^2 emanating at 3.35 $pCi/m^2/sec$, the total radon source rate would be 9.44×10^5 pCi/hr. Conservatively estimating a ventilation rate of 1.0 ach for this very leaky house, a building volume of 709 m^3, and using the following steady-state concentration model for a single well-mixed zone:

$$C_\infty = \frac{S}{IV} ;$$

where C_∞ = Steady state concentration (pCi/l),

I = Ventilation Rate (hr^{-1}),

V = Building Volume (l),

S = Radon Entry Rate (pCi/hr),

the indoor air concentration is calculated to be 1.3 pCi/l. While this value is close to the concentration in summer, it probably grossly overestimates the actual concentrations due to these sources, since ventilation rates are likely higher, average flux rates lower, and the indoor air concentrations are measured in a loosely coupled, separate zone. Even if the higher (and possibly erroneous) wall exhalation rate were used for the calculation, the predicted indoor radon concentrations would still only be 2.8 pCi/l.

Since even this worst case analysis does not indicate that building materials or the domestic water supply are the primary sources, it implies that the high indoor concentrations are due to convective flow of soil gas which is related to the local subsurface soil composition and structure [12]. A grab sampling of soil gas at ten of the homes during December 1985, shows relatively low radon levels (Table II.). The one Vancouver, WA site (EVA604) has concentrations very close to those in the Valley/Prairie homes. When these concentrations combine with high soil air permeability and adequate soil-to-house leakage area, the mechanism for high indoor concentrations can be explained.

The gravelly soil of the Valley/Prairie resulted from the outwash of glacially-dammed Lake Missoula following the retreats of the Cordilleran ice sheet 18000 - 13000 years ago. Deposits are reported to be over 25 meters in depth. Visual inspection indicates that the soil is loosely packed and likely to be highly permeable. Data from soil air permeability measurements were not yet available for preparation of this report.

In order to account for the observed indoor concentrations, a sizable quantity of soil gas must be entering the structures. For example, approximately 20% of the infiltrating air in house ESP120 must be soil gas. If we assume a ventilation rate of 1.0 ach for this 464 m^3 house, the soil gas entry rate would be approximately 93 m^3/hr. Suspecting that the grab samples near the house are depleted due to diffusion to the soil surface and the pumping action of the house, maximum soil gas radon concentrations at depths more typical of basement floors (2 meters) were calculated from:

$$C_\infty = \frac{\rho e}{\epsilon}$$

where: ρ, soil density, was taken to be 1.4 g/cm^3; e, emanating radon concentration from local samples was 0.20 pCi/g, and ; ϵ, soil porosity was assumed to be 0.4 cm^3 (air)/cm^3 (soil), yielding C_∞ of 700 pCi/l. Therefore, the grab samples fairly represent actual soil radon concentrations. Other houses, with lower indoor concentrations, can also be shown to have relatively high entry rates; house ESP111 with a volume 571 m^3 would have an estimated 5% (29 m^3/hr) of its infiltrating air as soil gas.

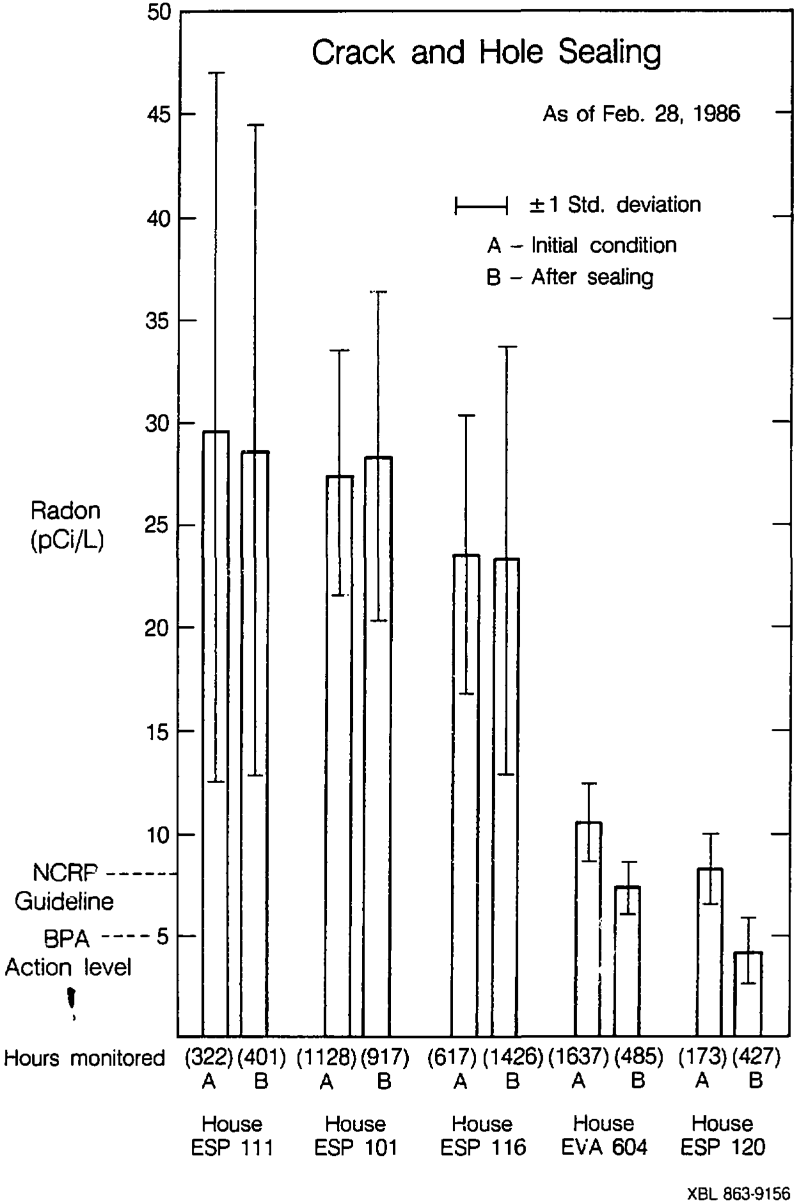
RESULTS FROM MITIGATION PROCEDURES

Following is a brief discussion of each mitigation technique. Figures 1. through 5. summarize the results of the data collected to date, which will be updated as the investigation continues.

Sealing of Cracks and Holes.

The sealing of floor-wall joints, floor and wall cracks, gaps around service penetrations, and holes from poorly laid slabs has reduced indoor radon concentration very slightly, if at all (Figure 1.). It may be that because generally only a small portion of the total crack and hole area is visible and accessible and therefore repairable, relatively little effect should be expected. Another factor could be that the resistance to flow through the soil is much greater than the resistance to flow through all cracks. This suggests that sealing actions would begin to be effective once the total substructure crack resistance has been increased to a value similar to that of the soil resistance. An exception appears to be house ESP120, where the difference between the before and after conditions (8.2 $\pm$ 1.82 S.D. pCi/l versus 4.1 $\pm$ 1.68 S.D. pCi/l) may be significant. However, these data are from a time period with a separate sub-surface

Figure 1.


Crack and Hole Sealing
As of Feb. 28, 1986
±1 Std. deviation
A – Initial condition
B – After sealing
Radon (pCi/L)
50
45
40
35
30
25
20
15
10
5
NCRP Guideline
BPA Action level
Hours monitored
(322) A
(401) B
(1128) A
(917) B
(617) A
(1426) B
(1637) A
(485) B
(173) A
(427) B
House ESP 111
House ESP 101
House ESP 116
House EVA 604
House ESP 120
XBL 863-9156

ventilation system operating, which may simply indicate that sealing improved the performance of this system. The reduction observed in house EVA604 where 18.5 meters of floor crack were sealed, may also be significant, although corrections for differing environmental conditions have not been made for either house. No reductions from sealing have been seen in any of the three houses where pre-sealing concentrations were above 20 pCi/l.

Disadvantages of this technique include:

1) difficulty in determining if a surface defect (e.g., crack) penetrates the entire thickness of the material;

2) the inability to access the majority of the substructure defects, especially in finished basements;

3) work can be labor intensive, in particular, if finished surfaces are to be repaired; and

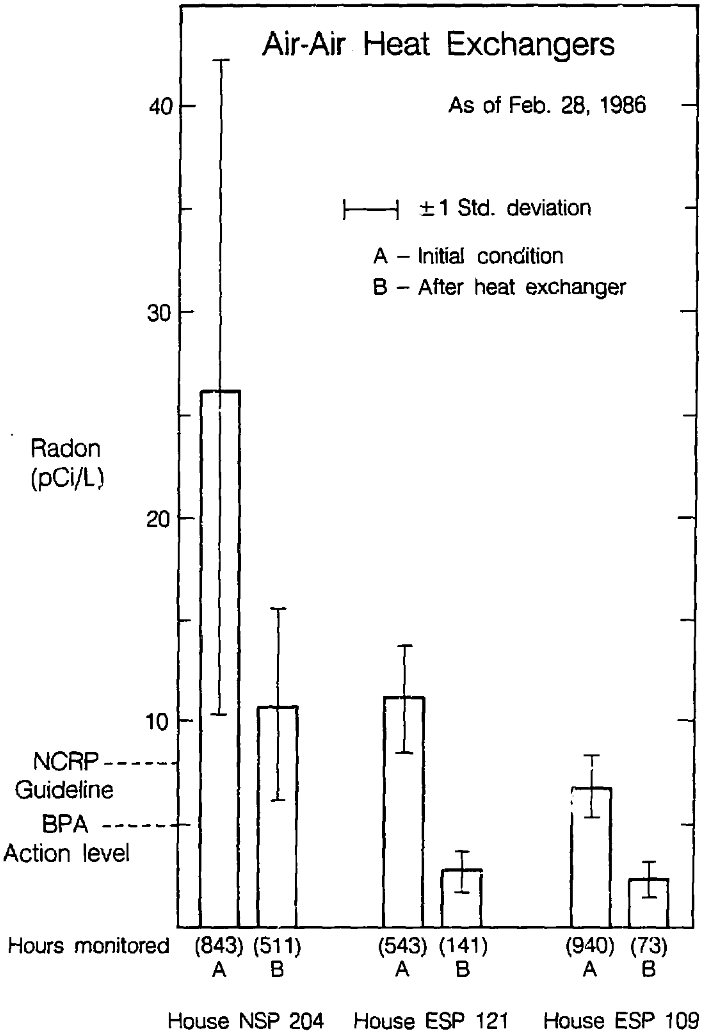
4) the unknown durability of the patch when subjected to normal aging and additional substructure movement.

House Ventilation with Heat Recovery.

The use of air-to-air heat exchangers in three homes has shown that the technique is suitable in lowering indoor levels (Figure 2.). In two of the homes (ESP121, ESP109), the new, ducted, central ventilation/heat exchange systems were sized to add approximately 1.0 ach of ventilation. Since the radon obviously enters the house via the basement, both systems were installed to supply air to and return air from two basement locations. At this point, the data represent a variety of supply and return flow rates. Reductions of almost 75%, from 11.2 pCi/l to 2.9 pCi/l, have been achieved in ESP121, and a reduction from 6.9 pCi/l to 2.3 pCi/l in ESP109. At these levels, we consider the technique to be successful.

House NSP204 is a new (1984) energy-efficient home built according to BPA's model conservation standards (MCS) that require the installation of an air-to-air heat exchanger in these low air leakage homes. In its original condition, the AAHX, located in the crawlspace, returned air from the upstairs, but only supplied air to the crawlspace and separate atrium. A more efficient circulation system was installed. Supply air has been delivered to the basement and atrium. Return air comes from only the atrium, upstairs bathroom and heated crawlspace. Levels were observed to fall from 26.3 pCi/l to 10.8 pCi/l. Additional work is planned for other ducting and delivery modifications.

Figure 2.



XBL 863-9157

Disadvantages of the use of air-to-air heat exchangers include:

1) high initial cost for the installation of a ducted central unit (wall and window units with proper freeze protection are under development and may be more economical to install);

2) additional annual energy costs of roughly $100 are predicted in the Spokane area; and

3) maintenance of a fairly complex system that requires frequent changing of filters, oiling of blowers, and annual cleaning of the heat exchanger core;

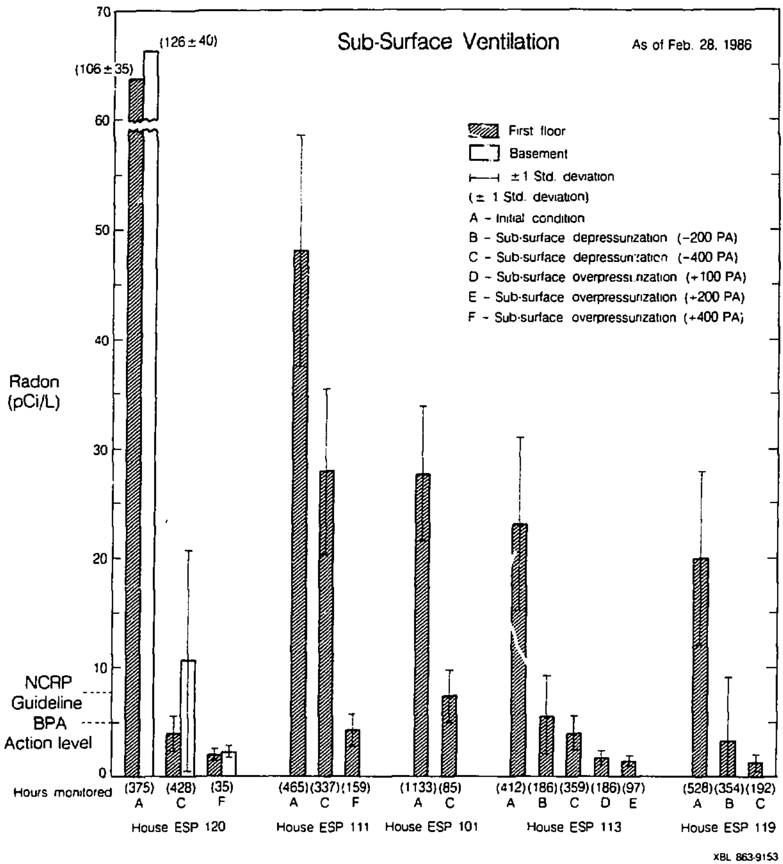
Sub-Surface Ventilation.

As seen in Figure 3., the effect of sub-surface ventilation (SSV) is dramatic. In no case has a SSV system, or modification of a SSV system failed to lower concentrations below the target of 5 pCi/l. The surprising discovery is that sub-surface overpressurization has been more effective than subsurface depressurization in the three homes where it has been attempted (ESP111, ESP113, ESP120).

House ESP120, with the highest initial concentrations of the study (132 pCi/l upstairs), had four ventilation pipes placed through the slab around the basement. On full depressurization, with a negative pressure of -400 pascals in the pipe at the soil relative to the basement atmosphere and a total flow of 94 l/s, average first floor concentrations of 5.2 pCi/l were measured while basement concentrations averaged 8.4 pCi/l. All of the pipes were contributing to the reduction since, as each was closed off on a rotating basis, radon concentrations increased. A preliminary sulfur hexafluoride (SF_6) tracer experiment mixed SF_6 in the basement, with the SSV systems operating, and observed SF_6 in the ventilation pipes at concentrations similar to those of the basement air (~50 ppm). Apparently most of the air in the SSV pipes is originating in the basement, then is drawn through the floor and walls into the soil and finally exhausted along with a small fraction of soil gas. This supports our presumption of the presence of a large total area of cracks and holes. When the direction of the blowers was reversed and outside air was blown into the soil below the slab, further reductions to 1.9 pCi/l upstairs and 2.1 pCi/l basement were observed for the very short monitoring period of 35 hours.

House ESP101 also had significant reductions from 27.6 pCi/l to 7.4 pCi/l upstairs after four SSV pipes were installed and depressurized. One pipe has since been disconnected with no change in radon concentrations. The system has been switched to overpressurization, but results are not yet available.

Figure 3.


Sub-Surface Ventilation
As of Feb. 28, 1986
(106±35)
(126±40)
First floor
Basement
±1 Std. deviation
(± 1 Std. deviation)
A - Initial condition
B - Sub-surface depressurization (-200 PA)
C - Sub-surface depressurization (-400 PA)
D - Sub-surface overpressurization (+100 PA)
E - Sub-surface overpressurization (+200 PA)
F - Sub-surface overpressurization (+400 PA)
Radon (pCi/L)
70
60
50
40
30
20
10
0
NCRP Guideline
BPA Action level
Hours monitored
(375) (428) (35)
A C F
House ESP 120
(465) (337) (159)
A C F
House ESP 111
(1133) (85)
A C
House ESP 101
(412) (186) (359) (186) (97)
A B C D E
House ESP 113
(528) (354) (192)
A B C
House ESP 119
XBL 863-9153

The largest improvement from switching to overpressurization occurred in house ESP111 where SSV depressurization in two pipes dropped upstairs levels from 47.9 pCi/l to 27.8 pCi/l and overpressurization further reduced levels to 4.2 pCi/l. Additional pipes have been installed to assure still lower concentrations.

Of all five homes where pipes have been installed, house ESP113 is the only one that has gravel underlying the concrete slab floor. As a result, the installation of one SSV pipe was sufficient for efficient sub-surface ventilation. Under depressurization of -200 pascals, the upstairs radon levels decreased from 23.0 pCi/l to 5.6 pCi/l, while an overpressurization of -200 pascals lowered levels even more, to 1.3 pCi/l.

Two pipes for sub-surface depressurization were installed along the exterior of a half-depth basement foundation wall in house ESP119. Sealing and ventilation of the crawlspace had already reduced upstairs radon concentrations from 49.4 pCi/l to 19.9 pCi/l, but scintillation flask sampling detected high concentrations in several basement wall cavities. The installation of the SSV system, operating at an underpressure of 200 pascals, has diminished radon to 3.3 pCi/l. SSV overpressurization has not been implemented at this house because of concerns about cold outside air, unheated by the house, freezing the soil around the footer and foundation.

A possible explanation of the advantage of SSV overpressurization for highly permeable, low emanation rate soils follows. At equal underpressures and overpressures (and flow rates) produced by an SSV system, similar pressure fields, represented by similar isobars, but with opposite pressures with respect to the basement, would be created near a house substructure. In the depressurization system, the negative pressures in the soil will cause air from the house to be pulled into the soil, at least until a point is reached at some distance from the pipe(s) where the underpressure has been diminished so that soil pore and house pressures are equal. Beyond that point, any crack in the substructure will allow the higher pressure, radon-bearing soil gas to enter the house. Thus, to eliminate all soil gas entry, the depressurization system must cause an underpressure around the entire understructure of the house.

On the other hand, the SSV overpressure system will create a positive pressure field in the soil that always causes air to flow from the soil into the house through cracks in the substructure. However, the positive pressure field also inhibits the transport radon from a distance. Together with a net flow of comparatively fresh air from the pipe at the house into the soil, radon concentrations in the soil gas are diluted. The overpressure system may still be effective (where the depressurization system begins to fail) because, although air is passing into the house from the soil, it is relatively low in radon concentration. The overpressure system possibly fails at the point where the pressure field has decreased to equal the pressure of the surrounding soil. At this point, ventilation and dilution are no longer taking place. The overpressure system may depend on the fact that a parcel of fresh outside air from the SSV pipe that re-enters the house, picks up only a small amount of radon from the soil it is passing through. In other words, a short residence time of the parcel in the soil (as determined by the soil path length, permeability, and pressure difference) and a low soil radium concentration may be necessary for the overpressure system to be effective. A thorough evaluation of this interpretation with supporting laboratory and field measurements are required.

Disadvantages of the use of sub-surface ventilation include:

1) the cost, effort, and disruption of installing ventilation pipes through concrete slabs;

2) difficulty in locating blowers that develop sufficiently high pressure heads with moderate flow rates at low energy use rates;

3) maintaining the blowers for quiet and efficient long-term operation (periodic replacement will be necessary);

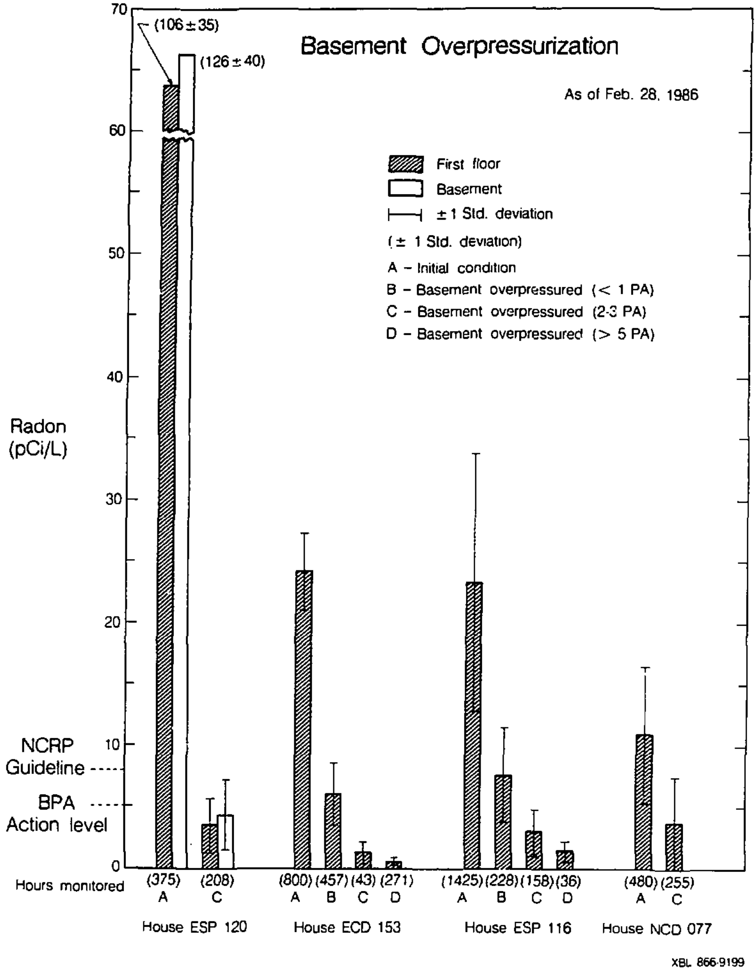
4) possible water vapor condensation on the SSV depressurization pipes in the summer and the SSV overpressurization pipes in the winter; and

5) the risk of freezing the soil, water pipes or drain pipes below the slab when using a SSV overpressurization system (colder slab floors and increased heat loss through the floor may also result).

Basement Overpressurization.

In four homes, a blower pulling air from a heated upper floor, pressurizes the basement space with respect to the soil pores. This reversal of the indoor-outdoor pressure differential inhibits convective flow of soil gas into the basement (Figure 4.) In the homes in this study, basement overpressures of approximately 2-3 pascals appear to be sufficient for reducing radon levels below 5 pCi/l. For houses ESP116 and ECD153, where a range of overpressures were tested, upstairs radon levels fell from 23-24 pCi/l to 7.6 pCi/l (ESP116) and 6.0 pCi/l (ECD153) at pressures only slightly over neutral (< 1 pascal). At approximately 3 pascals overpressure, radon concentrations were decreased to 2.9 pCi/l (ESP116) and 1.2 pCi/l (ECD153). At overpressures greater than 5 pascals, indoor concentrations were even lower - 1.4 pCi/l (ESP116) and 0.5 pCi/l (ECD153). These low pressure measurements are difficult to make, since they are in the range of noise resulting from natural factors such as wind and door closings. The values presented here are uncorrected for temperature differences in the sample tubes, yet pressure measurements under natural conditions indicate that the substructures were originally underpressured by from 2-6 pascals, typical of the values calculated due to stack effect.

Figure 4.


Basement Overpressurization
As of Feb. 28, 1986
First floor
Basement
± 1 Std. deviation
(± 1 Std. deviation)
A – Initial condition
B – Basement overpressured (< 1 PA)
C – Basement overpressured (2-3 PA)
D – Basement overpressured (> 5 PA)
(106 ± 35)
(126 ± 40)
Radon (pCi/L)
NCRP Guideline
BPA Action level
0
10
20
30
40
50
60
70
Hours monitored
(375) A
(208) C
(800) A
(457) B
(43) C
(271) D
(1425) A
(228) B
(158) C
(36) D
(480) A
(255) C
House ESP 120
House ECD 153
House ESP 116
House NCD 077
XBL 866-9199

Fan flow rates from 118 to 189 l/s were necessary to develop the 3 pascal overpressurization. Since the required flow is very dependent on the leakage of the basement shell, holes in the exterior walls as well as the basement ceiling to the upper floors were sealed.

This technique was first tested in homes with forced air furnaces that could be operated continuously and easily unbalanced to deliver more air to the basement than upper floors. Unfortunately, the large furnace blower was not suited for this task, causing poor heat distribution, excessive air movement throughout the house, noise, high electrical consumption, and backdrafting in upstairs wood stoves and fireplaces. However, these simple tests proved the effectiveness of the general technique. Ironically, homes with forced air furnaces may be the most difficult to pressurize with an independent blower because the ductwork provides a low resistance path for air flow throughout the building spaces. This problem is addressed by installing a separate fan that pulls air from the cold air return of the furnace, sealing the basement cold air return, and installing a backdraft damper in the main furnace supply. These methods restrict the recirculation of air in the basement supply and return ducting and take advantage of the ducting to pull air from the upstairs return register.

Disadvantages of basement pressurization include:

1) implementation is possible only in basements with a tight shell and a closeable door;

2) basement overpressurization can be easily destroyed by occupants opening basement windows or doors (occupants must be thoroughly familiar with the concept of the system);

3) maintaining the blowers for long-term quiet and efficient operation (periodic replacement will be necessary);

4) avoiding excessive upstairs depressurization that can cause backdrafting of combustion-fired appliances and cold drafts from infiltrating air;

5) unintentional heating of basements with attendant additional heat loss;

6) the overall house ventilation rate may increase and lead to larger heating and cooling loads (it may be that some of the reduction in radon concentrations is a result of this increased ventilation);

7) the potential for moisture damage to house structural components from the forced exfiltration of warm, moist indoor air.

Crawlspace Sealing and Ventilation.

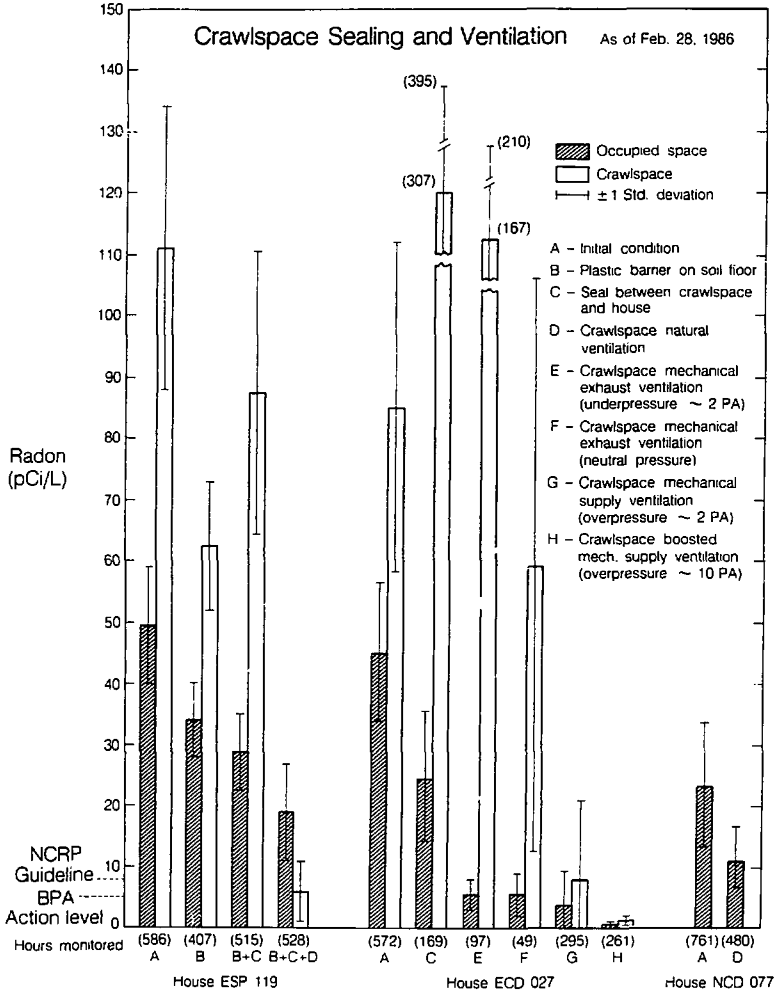
Figure 5. summarizes the results of tests of this technique. No home in this study is exclusively underlaid by a typical crawlspace. Houses ESP119 and NCD077 have both a crawlspace and basement, each of which contributes radon to the building. In house ESP119, the total of all crawlspace techniques reduced first floor radon levels from 49.4 pCi/l to 19.9 pCi/l, which was later reduced by an exterior basement SSV depressurization system (see Figure 5.). In house NCD077, original first floor radon levels of 23.3 pCi/l were reduced by crawlspace ventilation to 10.8 pCi/l, which was later decreased to 3.7 pCi/l after basement overpressurization. Work was staged in house ESP119, so that the crawlspace concrete walls and soil floor were first sealed with a plastic membrane which reduced concentrations in the house to 34.0 pCi/l and in the crawlspace from 111.4 pCi/l to 62.5 pCi/l. In fact, bulk soil gas entry caused this tight, lightweight plastic membrane to fill and "balloon" until it eventually occupied one half the volume of the crawlspace. This undesirable side effect was alleviated by adding the weight of boards and planking on top of the plastic. The second stage, sealing of the house from the crawlspace, diminished house concentrations to 28.8 pCi/l, but increased the crawlspace concentrations to 87.4 pCi/l. The final stage, natural ventilation of the crawlspace, lowered house concentrations to 19.9 pCi/l and crawlspace concentrations to 6.2 pCi/l.

House ECD027 is atypical in that the "crawlspace" is actually an unused, unheated, soil floor basement. Originally, a forced air wood furnace was located in this space, and large openings were present between this basement and the first floor. The first remedial action combined removing the furnace and placing a wood stove on the first floor with sealing of all openings between the basement and upstairs. The sealing included floor insulation and installation of a membrane of Tyvek® below the insulation to prohibit air infiltration from the basement to the upstairs yet allowing moisture to pass out of the insulation. This work reduced house radon concentrations from 45.0 pCi/l to 24.5 pCi/l and increased basement levels from 85.0 pCi/l to 307 pCi/l.

The house construction limited the number of basement vents for natural ventilation and concentrations were reduced only marginally, to 21.2 pCi/l in the house and 208 pCi/l in the basement. By adding 80 l/s of mechanical exhaust ventilation to the basement, the basement was slightly underpressured (~2 pascals) and house concentrations decreased to 5.4 pCi/l, while radon entry into the basement increased yielding a basement concentration of 167 pCi/l.

Next, basement pressures were neutralized by adding vent area while the ventilation flow rate remained the same. House concentrations did not change (5.4 pCi/l) and basement levels dropped to 59.3 pCi/l. Then by reversing the blower and maintaining the same flow rate, the basement was slightly overpressured (~2 pascals) so that house levels fell to 3.9 pCi/l and radon entry into the basement was reduced, as indicated by a basement a concentration of 8.1 pCi/l.

Figure 5.



XBL 866-2206

The final configuration incorporates a 60 watt axial fan that has boosted the basement overpressure to -10 pascals and lowered upstairs radon concentrations to 0.4 pCi/l and basement radon levels to 1.3 pCi/l.

Disadvantages of this technique are few, since the additional ventilation also helps to remove moisture from the crawlspace (basement). While the data from the sealing techniques is informative, the ventilation by itself will eliminate most of the radon from the crawlspace.

SUMMARY

Preliminary findings have identified several promising radon control techniques that include basement overpressurization, sub-surface ventilation by depressurization and overpressurization, and crawlspace ventilation.

All techniques, properly applied, are capable of reducing radon levels in these homes below any existing guideline for radon concentrations. Basement pressurization may be a low-cost solution in homes with tight, closeable basements, but may be easily defeated through occupant interference. Sub-surface depressurization is labor intensive and may require special blowers, yet it may provide an effective and reliable long-term solution. Surprisingly, sub-surface pressurization was more effective than identical depressurization systems, but may be suitable for only certain soil conditions. Crawlspace ventilation is still an essential method of control in homes with crawlspaces, but may not entirely eliminate radon in homes that also have basements contributing to the indoor concentration. Ventilation with air-to-air heat exchangers appears to be effective in homes with low initial ventilation rates or low initial radon concentrations. Sealing of cracks and holes between the soil and the basement has been generally ineffective.

As this investigation continues, additional information including cost of installations will become available.

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